Aries
(Lecture 6, cs262a)

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February 5, 2018

(based on slide from Joe Hellerstein and Alan Fekete)

Today’s Paper

ARIES: A Transaction Recovery Method Supporting Fine-Granularity Locking and Partial Rollbacks Using Write-ahead Logging, C. Mohan, Don Haderle, Bruce Lindsay, Hamid Pirahesh and Peter Schwarz. Appears in Transactions on Database Systems, Vol 17, No. 1, March 1992, Pages 94-162

Thoughts?

Review: The ACID properties

Atomicity: All actions in the Transaction happen, or none happen

Consistency: If each Transaction is consistent, and the DB starts consistent, it ends up consistent

Isolation: Execution of one Transaction is isolated from that of other Transactions

Durability: If a Transaction commits, its effects persist

The Recovery Manager guarantees Atomicity & Durability

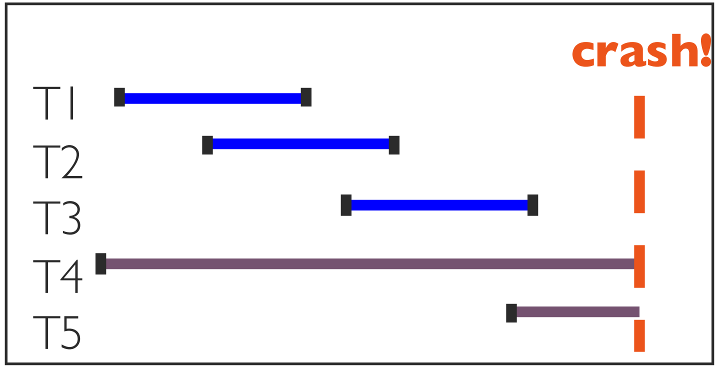
Motivation

Atomicity:

- Transactions may abort ("Rollback")

Durability:

- What if DBMS stops running? (Causes?)
- Desired Behavior after system restarts:
  - T1, T2 & T3 should be durable
  - T4 & T5 should be aborted (effects not seen)



Intended Functionality

At any time, each (visible) data item contains the value produced by the **most recent update** done by a **transaction that committed**

Goals

1. Simplicity
2. Operation logging (example?)
3. Flexible storage management
4. Partial rollbacks
5. Flexible buffer management
6. Recovery independence
7. Logical undo
8. Parallelism and fast recovery
9. Minimal overhead

Assumptions

Essential concurrency control is in effect

- For read/write items: Write locks taken and held till commit
  - E.g., Strict 2PL, but read locks not important for recovery
- For more general types: operations of concurrent transactions commute

Updates are happening "in place"

- i.e. data is overwritten on (or deleted from) its location
  - Unlike multiversion (e.g., shadow pages) approaches

Buffer in volatile memory

Data persists on disk

Challenge: REDO

Action	Buffer	Disk
Initially		0
T1 writes 1	1	0
T1 commits	1	0
CRASH		0

Need to restore value 1 to item

- Last value written by a committed transaction

Challenge: UNDO

Action	Buffer	Disk
Initially		0
T1 writes 1	1	0
Page flushed		1
CRASH		1

Need to restore value 0 to item

- Last value from a committed transaction

Handling the Buffer Pool

What is a simple scheme to guarantee Atomicity & Durability?

Force write to disk at commit?

- Poor response time
- But provides durability

No Steal of buffer-pool frames from uncommited Transactions (“pin”)?

- Poor throughput
- But easily ensure atomicity

	No Steal	Steal
Force	Trivial	
No Force		Desired

More on Steal and Force

STEAL (why enforcing Atomicity is hard)

- *To steal frame F:* Current page in F (say P) is written to disk; some Transaction holds lock on P
  - What if the Transaction with the lock on P aborts?
  - Must remember old value of P at steal time (to support UNDOing the write to page P)

NO FORCE (why enforcing Durability is hard)

- What if system crashes before a modified page is written to disk?
- Write as little as possible, in a convenient place, at commit time, to support REDOing modifications

Basic Idea: Logging

Record REDO and UNDO information, for every update, in a *log*

- Sequential writes to log (put it on a separate disk)
- Minimal info (diff) written to log, so multiple updates fit in a single log page

Log: An ordered list of REDO/UNDO actions

- Log record contains:

  <XID, pageID, offset, length, old data, new data>

- and additional control info (which we'll see soon)
- For abstract types, have operation(args) instead of old value new value

Write-Ahead Logging (WAL)

The Write-Ahead Logging Protocol:

1. Must force the log record for an update *before* the corresponding data page gets to disk
2. Must write all log records for a Transaction *before commit*

#1 (undo rule) allows system to have Atomicity

#2 (redo rule) allows system to have Durability

ARIES

Exactly how is logging (and recovery!) done?

- Many approaches (traditional ones used in relational systems of 1980s)
- ARIES algorithms developed by IBM used many of the same ideas, and some novelties that were quite radical at the time
  - Research report in 1989; conference paper on an extension in 1989; comprehensive journal publication in 1992
  - 10 Year VLDB Award 1999

Key ideas of ARIES

Log every change (*even UNDOs during Transaction abort*)

In restart, *first* repeat history without backtracking

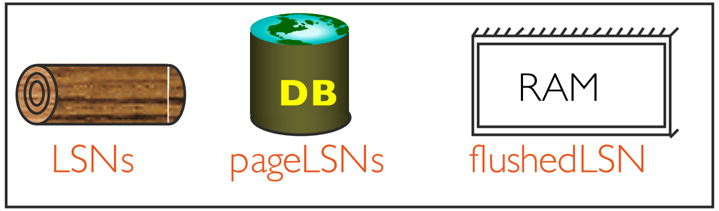
- *Even REDO the actions of loser transactions*

Then UNDO actions of losers

LSNs in pages used to coordinate state between log, buffer, disk

Novel features of ARIES *in italics*

WAL & the Log



Each log record has a unique Log Sequence Number (LSN)

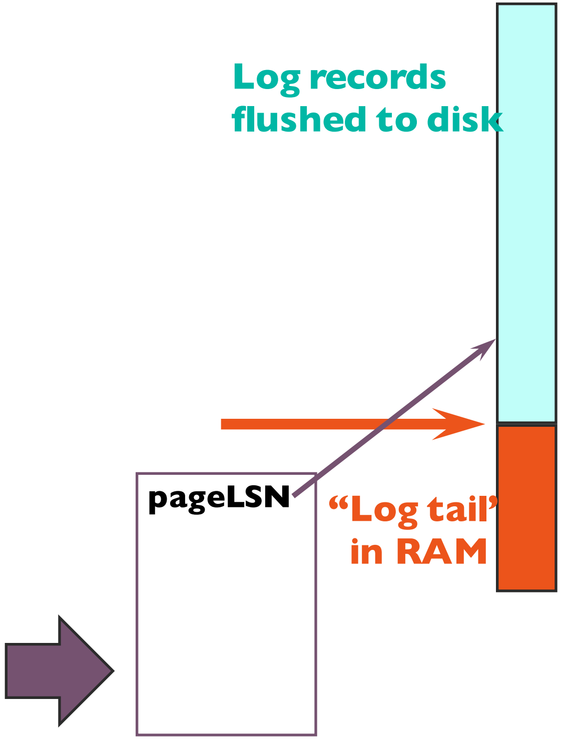
- LSNs always increasing

Each *data page* contains a pageLSN

- The LSN of the most recent *log record* for an update to that page

System keeps track of flushedLSN

- The max LSN flushed so far



WAL constraints

Before a page is written,

- pageLSN ≤ flushedLSN

Commit record included in log; all related update log records precede it in log

Log Records

LogRecord fields:

prevLSN
XID
type

$$\text{update records only}\left\{\begin{array}{l}\text{pageID}\\ \text{length}\\ \text{offset}\\ \text{before-image}\\ \text{after-image}\end{array}\right.$$

Possible log record types:

Update

Commit

Abort

End (signifies end of commit or abort)

Compensation Log Records (CLRs)

- for UNDO actions
- (and some other tricks!)

Other Log-Related State

Transaction Table:

- One entry per active Transaction
- Contains XID, status (running/commited/aborted), and lastLSN

Dirty Page Table:

- One entry per dirty page in buffer pool
- Contains recLSN – the LSN of the log record which *first* caused the page to be dirty

Normal Execution of a Transaction

Series of reads & writes, followed by commit or abort

- We will assume that page write is atomic on disk
  - In practice, additional details to deal with non-atomic writes

Strict 2PL (at least for writes)

STEAL, NO-FORCE buffer management, with Write-Ahead Logging

Checkpointing

Periodically, the DBMS creates a checkpoint, in order to minimize the time taken to recover in the event of a system crash. Write to log:

- begin_checkpoint record: Indicates when chkpt began.
- end_checkpoint record: Contains current *Transaction table* and *dirty page table*. This is a `fuzzy checkpoint':
  - Other Transactions continue to run; so these tables only known to reflect some mix of state *after the time of the begin_checkpoint record*.
  - No attempt to force dirty pages to disk; effectiveness of checkpoint limited by oldest unwritten change to a dirty page. (So it's a good idea to periodically flush dirty pages to disk!)
- Store LSN of chkpt record in a safe place (*master* record)

The Big Picture: What's Stored Where

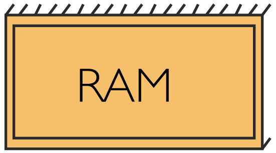
LogRecords

prevLSN
XID
type
pageID
length
offset
before-image
after-image

Data pages

each
with a
pageLSN

master record



Transaction Table

lastLSN
status

Dirty Page Table

recLSN

flushedLSN

Simple Transaction Abort

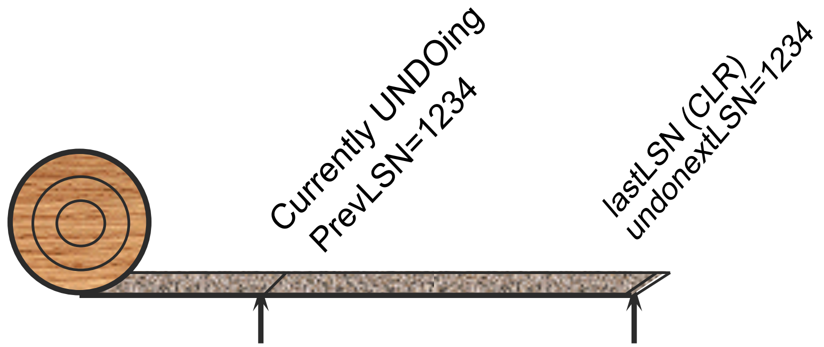
For now, consider an explicit abort of a Transaction

- No crash involved

We want to "play back" the log in reverse order, UNDOing updates.

- Get lastLSN of Transaction from Transaction table
- Can follow chain of log records backward via the prevLSN field
- Note: before starting UNDO, could write an *Abort* log record
  - Why bother?

Abort, cont



To perform UNDO, must have a lock on data!

- No problem!

Before restoring old value of a page, write a compensation log record (CLR):

- You continue logging while you UNDO!!
- CLR has one extra field: undonextLSN
  - Points to next LSN to undo (i.e. prevLSN of the record we're currently undoing)
- CLR contains REDO info
- CLRs *never* Undone
  - Undo needn't be idempotent (>1 UNDO won't happen)
  - But they might be Redone when repeating history (=1 UNDO guaranteed)

At end of all UNDOs, write an "end" log record

Transaction Commit

Write commit record to log

All log records up to Transaction's lastLSN are flushed

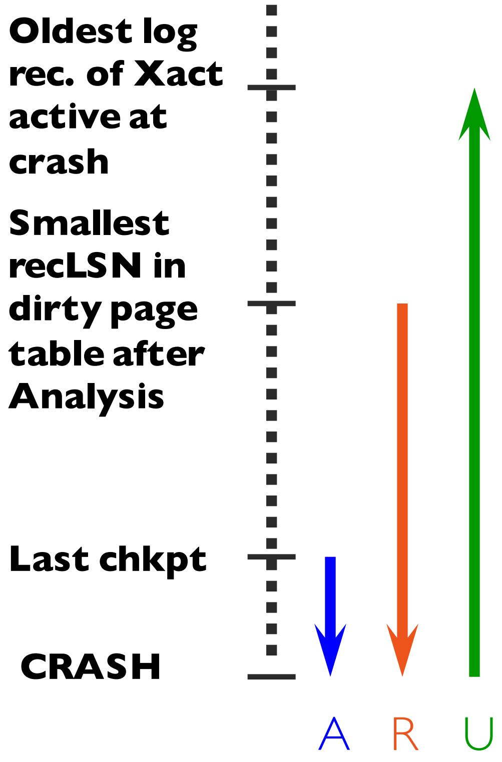
- Guarantees that flushedLSN ≥ lastLSN
- Note that log flushes are sequential, synchronous writes to disk
- Many log records per log page

Make transaction visible

- Commit() returns, locks dropped, etc.

Write end record to log

Crash Recovery: Big Picture


Oldest log rec. of Xact active at crash
Smallest recLSN in dirty page table after Analysis
Last chkpt
CRASH
A
R
U

- Start from a checkpoint (found via master record)
- Three phases. Need to:
  - Figure out which Xacts committed since checkpoint, which failed (Analysis)
  - REDO ***all*** actions
    - (repeat history)
  - UNDO effects of failed Xacts.

Recovery: The Analysis Phase

Reconstruct state at checkpoint

- via end_checkpoint record

Scan log forward from begin_checkpoint

- End record: Remove Xact from Xact table
- Other records: Add Xact to Xact table, set lastLSN=LSN, change Xact status on commit
- Update record: If P not in Dirty Page Table (DPT)
  - Add P to DPT., set its recLSN=LSN

This phase could be skipped;
information can be regained in subsequent REDO pass

Recovery: The REDO Phase

We *repeat History* to reconstruct state at crash:

- Reapply *all* updates (even of aborted Xacts!), redo CLRs

Scan forward from log rec containing smallest recLSN in DPT. For each CLR or update log rec LSN, REDO the action unless page is already more up-to-date than this record:

- REDO when Affected page is in D.P.T., and has pageLSN (in DB) < LSN. (if page has recLSN > LSN no need to read page in from disk to check pageLSN)

To REDO an action:

- Reapply logged action
- Set pageLSN to LSN. No additional logging!

Invariant

State of page P is the outcome of all changes of relevant log records whose LSN is <= P.pageLSN

During redo phase, every page P has P.pageLSN >= currently-redoing-LSN

Thus at end of redo pass, the database has a state that reflects exactly everything on the (stable) log

Recovery: The UNDO Phase

Key idea: Similar to simple transaction abort, for each loser transaction (that was in flight or aborted at time of crash)

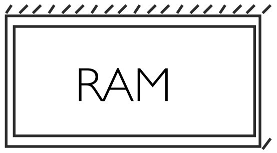
- Process each loser transaction's log records backwards; undoing each record in turn and generating CLRs

But: loser may include partial (or complete) rollback actions

Avoid undo-ing what was already undone

- undoNextLSN field in each CLR equals prevLSN field from the original action

Example of Recovery



Xact Table

lastLSN

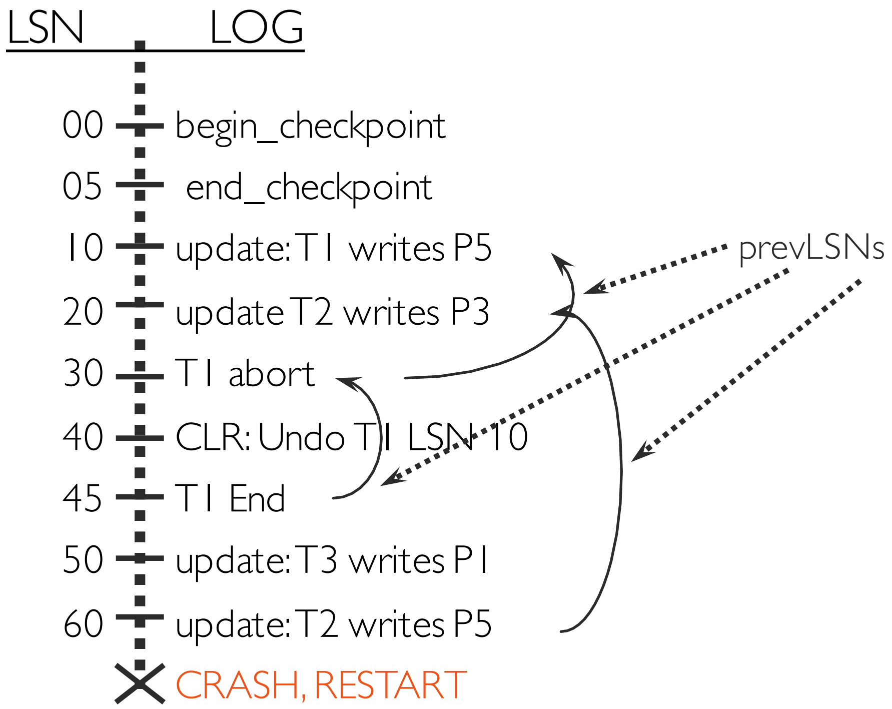
status

Dirty Page Table

recLSN

flushedLSN

ToUndo



LSN	LOG
00	begin_checkpoint
05	end_checkpoint
10	update: T1 writes P5
20	update T2 writes P3
30	T1 abort
40	CLR: Undo T1 LSN 10
45	T1 End
50	update: T3 writes P1
60	update: T2 writes P5
	CRASH, RESTART

Example: Crash During Restart!

RAM

Xact Table

lastLSN

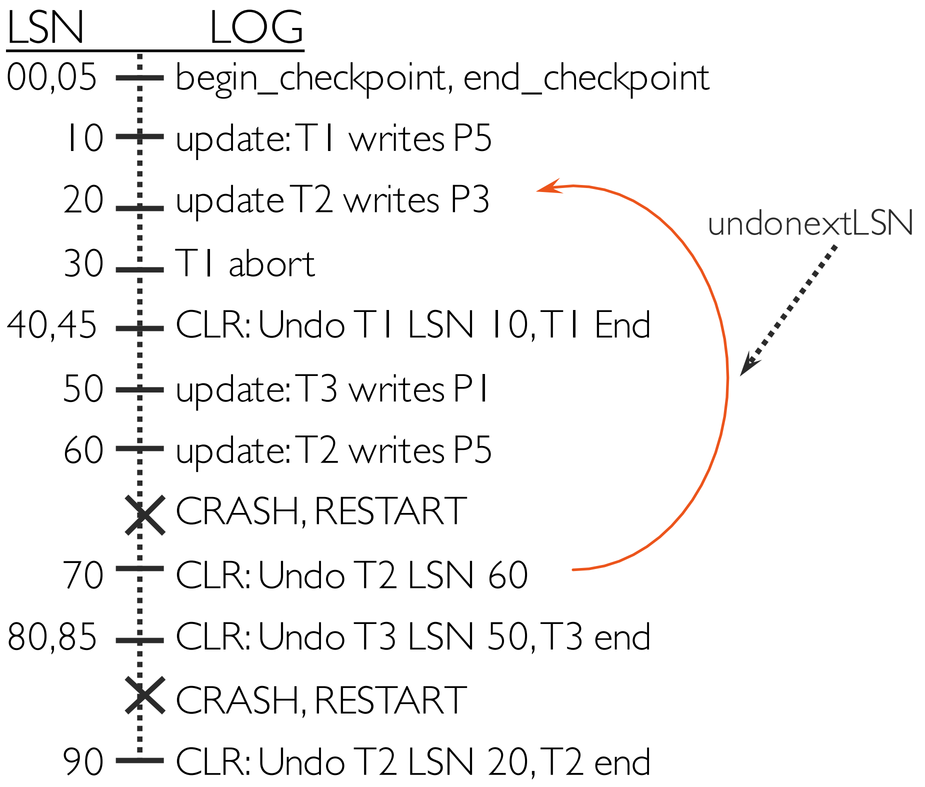
status

Dirty Page Table

recLSN

flushedLSN

ToUndo



LSN	LOG
00,05	begin_checkpoint, end_checkpoint
10	update: T1 writes P5
20	update T2 writes P3
30	T1 abort
40,45	CLR: Undo T1 LSN 10, T1 End
50	update: T3 writes P1
60	update: T2 writes P5
	CRASH, RESTART
70	CLR: Undo T2 LSN 60
80,85	CLR: Undo T3 LSN 50, T3 end
	CRASH, RESTART
90	CLR: Undo T2 LSN 20, T2 end

Additional Crash Issues

What happens if system crashes during Analysis? During REDO?

How do you limit the amount of work in REDO?

- Flush asynchronously in the background.
- Watch “hot spots”!

How do you limit the amount of work in UNDO?

- Avoid long-running Xacts.

Parallelism during restart

Remember the invariants!

Activities on a given page must be processed in sequence

Activities on different pages can be done in parallel

Log record contents

What is actually stored in a log record, to allow REDO and UNDO to occur?

Many choices, 3 main types

- PHYSICAL
- LOGICAL
- PHYSIOLOGICAL

Physical logging

Describe the bits (optimization: only those that change)

Example

- OLD STATE: 0x47A90E….
- NEW STATE: 0x632F00…
- So REDO: set to NEW; UNDO: set to OLD

Or just delta (OLD XOR NEW)

- DELTA: 0x24860E…
- So REDO=UNDO=xor with delta

Question: XOR is not idempotent, but redo and undo must be; why is this OK?

Logical Logging

Describe the operation and arguments

E.g., *Update field 3 of record whose key is 37, by adding 32*

We need a programmer supplied inverse operation to undo this

Physiological Logging

Describe changes to a specified page, logically within that page

Goes with common page layout, with records indexed from a page header

Allows movement within the page (important for records whose length varies over time)

E.g., on page 298, replace record at index 17 from old state to new state

E.g., on page 35, insert new record at index 20

ARIES logging

ARIES allows different log approaches; common choice is:

Physiological REDO logging

- Independence of REDO (e.g. indexes & tables)
  - Can have concurrent commutative logical operations like increment/decrement ("escrow transactions")

Logical UNDO

- To allow for simple management of physical structures that are invisible to users
  - CLR may act on different page than original action
- To allow for escrow

Interactions

Recovery is traditionally designed with deep awareness of access methods (eg B-trees) and concurrency control

And vice versa

Need to handle failure during page split, reobtaining locks for prepared transactions during recovery, etc

Summary of Logging/Recovery

Recovery Manager guarantees Atomicity & Durability.

Use WAL to allow STEAL/NO-FORCE w/o sacrificing correctness.

LSNs identify log records; linked into backwards chains per transaction (via prevLSN).

pageLSN allows comparison of data page and log records.

Summary, Cont.

Checkpointing: A quick way to limit the amount of log to scan on recovery.

Recovery works in 3 phases:

- Analysis: Forward from checkpoint.
- Redo: Forward from oldest recLSN.
- Undo: Backward from end to first LSN of oldest Xact alive at crash.

Upon Undo, write CLRs.

Redo “repeats history”: Simplifies the logic!

Further Readings

Repeating History Beyond ARIES,

- C. Mohan, Proc VLDB’99
- Reflections on the work 10 years later

Model and Verification of a Data Manager Based on ARIES

- D. Kuo, ACM TODS 21(4):427-479
- Proof of a substantial subset

A Survey of B-Tree Logging and Recovery Techniques

- G. Graefe, ACM TODS 37(1), article 1

Is this a good paper?

What were the authors’ goals?

What about the performance metrics?

Did they convince you that this was a good system?

Were there any red-flags?

What mistakes did they make?

Does the system meet the “Test of Time” challenge?

How would you review this paper today?

Backup

Nested Top Actions

Trick to support physical operations you do not want to ever be undone

- Example?

Basic idea

- At end of the nested actions, write a dummy CLR
  - Nothing to REDO in this CLR
- Its ore the
  nes

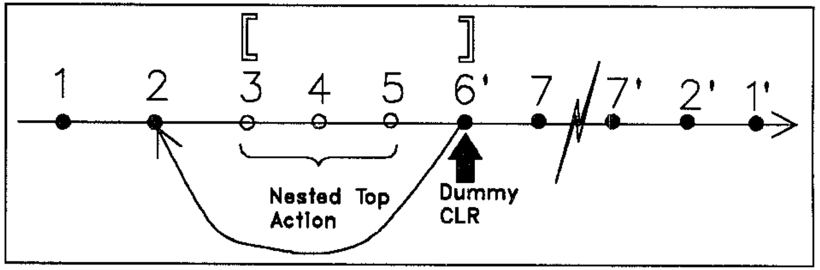


Fig. 14. Nested top action example.

Recovery: The UNDO Phase

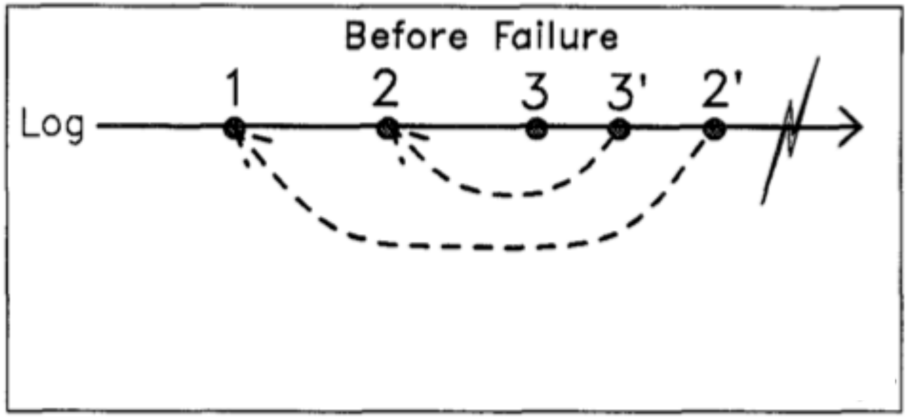
ToUndo={ *l* | *l* a lastLSN of a “loser” Xact}

Repeat:

- Choose largest LSN among ToUndo.
- If this LSN is a CLR and undonextLSN==NULL
  - Write an End record for this Transaction
- If this LSN is a CLR, and undonextLSN != NULL
  - Add undonextLSN to ToUndo
  - (Q: what happens to other CLRs?)
- Else this LSN is an update. Undo the update, write a CLR, add prevLSN to ToUndo

Until ToUndo is empty

UndoNextLSN



I′ is the Compensation Log Record for I
I′ points to the predecessor, if any, of I

Fig. 5. ARIES' technique for avoiding compensating compensations and duplicate compensations.

From Mohan et al, TODS 17(1):94-162

Restart Recovery Example

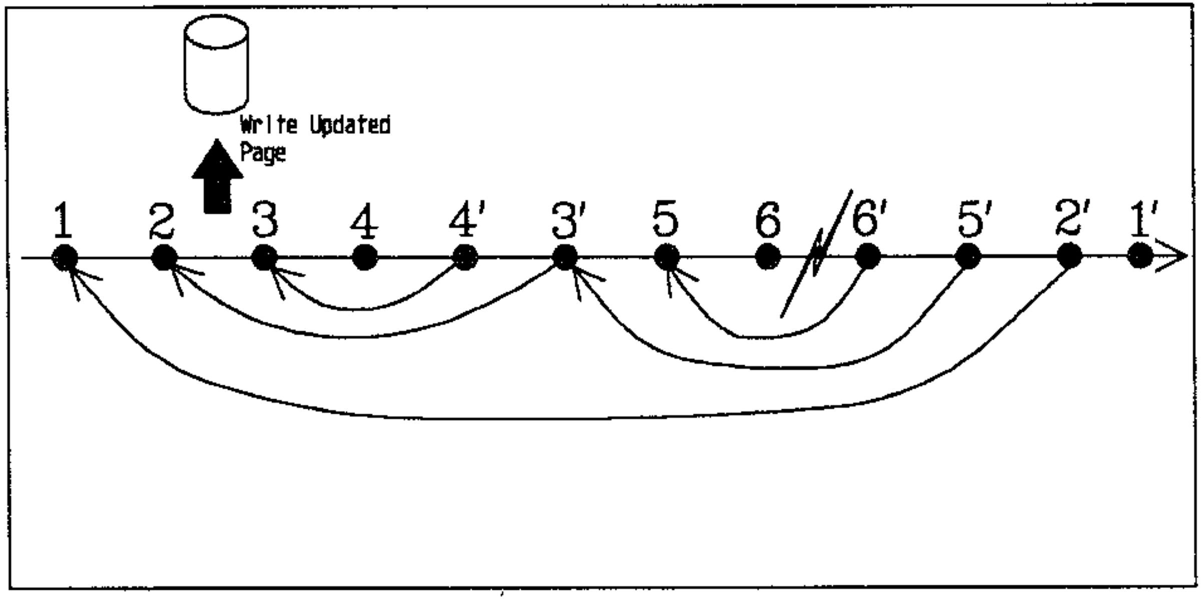


Fig. 13. Restart recovery example with ARIES.

From Mohan et al, TODS 17(1):94-162